The place and role of chernozems and regenerative agriculture in mitigating climate change and increasing adaptive capacity

La place et le rôle des tchernozioms et de l'agriculture régénératrice dans l'atténuation des changements climatiques et l'augmentation des capacités d'adaptation

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ABSTRACT: Despite the limited areas (725 million ha) of chernozems within the land, they contain about 8% of the global reserves of organic carbon contained in the pedosphere and account for about 10% of the global potential for sequestering organic carbon. At the same time, as a result of the degradation of arable chernozems (globally, about 31% of the total area of chernozems is included in the agricultural circuit), they have practically transformed from areas sequestering greenhouse gases into areas emitting them. In addition, their natural fertility has been significantly reduced and, respectively, the capacity to capture carbon dioxide from the atmosphere through plants. Solving this global problem requires changing the paradigm of agricultural chernozem management by placing emphasis on sequestering and stabilizing organic carbon in the soil within the framework of agrobiocenotic pedoregenerative agricultural technologies. At the same time, the theoretical principles of chernozem pedogenesis assume the management of the unidirectional regeneration process of the chernozem pedogenetic process within two successive natural-anthropogenic-evolutionary phases: a) rehabilitation and b) regeneration.
KEY WORDS: chernozems, organic carbon sequestration, humus mineralization.

RÉSUMÉ : Malgré leur superficie limitée (725 millions d'hectares), les tchernozioms renferment environ 8 % des réserves mondiales de carbone organique présentes dans la pédosphère et représentent près de 10 % du potentiel mondial de séquestration de ce carbone. Cependant, la dégradation des tchernozioms arables (environ 31 % de la superficie totale des tchernozioms est intégrée au circuit agricole) les a transformés, de zones de séquestration des gaz à effet de serre, en zones d'émission. La résolution de ce problème global exige un changement de paradigme dans la gestion agricole des tchernozioms, en privilégiant la séquestration et la stabilisation du carbone organique dans les sols, dans le cadre de technologies agricoles agrobiocénotiques et pédorégénératrices. Parallèlement, les principes théoriques de la pédogenèse des tchernozioms supposent la gestion d'un processus de régénération unidirectionnel au sein de ce processus, selon deux phases successives naturelles, anthropiques et évolutives : a) la réhabilitation et b) la régénération.
MOTS CLÉS : tchernozioms, séquestration de carbone organique, minéralisation de l'humus.

1. Introduction

The impact of climate change, manifested in extreme climatic phenomena such as heat waves, droughts, floods, etc., is increasingly serious and its consequences are increasingly felt and materialize in the intensification of soil degradation processes and their accelerated aridification.

Under these conditions, mitigating the effects of climate change and adapting to them are urgent, but also real given that soils have such a capacity. Through the prism of the theory of pedogenesis, the soil (pedosphere) mediates the exchange of substances and energy between the spheres of the Earth (atmosphere, climatosphere, biosphere, lithosphere, hydrosphere) and ensures the balance between the biological and geological carbon cycle.

In this context, the formation and breakdown of organic matter constitute a fundamental aspect of pedogenesis, reflected in the soil organic matter system whose quantitative and qualitative characteristics are expressed through humus reserves and the humus profile. The wide diversity of metabolic transformations of organic compounds during pedogenesis results in the development of distinct organic profiles across different biohydrothermal environments, giving the soil cover a characteristic mosaic structure and varying contributions to the organic carbon cycle. Therefore, the content and reserves of organic substances in soil represent key indicators of the direction and intensity of pedogenetic processes occurring in various soil types and subtypes, as well as their role within the organic carbon cycle.

In this context, a special place belongs to chernozems. According to the first global map of chernozems, the total area of chernozems on land is only 725 million ha, which is about 2% of the biologically productive land of the Earth and about 15% of the total area of soils cultivated by man. At the same time, interest in them is special through the prism of their priority role in mitigating the consequences of climate change and adapting to it, given that they contain 8.2% of the global reserves of organic matter contained in soils and can provide 10% of the global potential for sequestering organic carbon.

In this context, chernozems are ranked second, after swamp soils, in terms of the amount of carbon sequestered and stabilized in the soil, which is one of the basic global functions of ordinary chernozems with their high share in food production and ensuring food security for the population. At the same time, 543.7 million ha (75%) of chernozems are concentrated in countries (Russia, Mongolia, Colombia, Mexico, etc.) with a low level of practiced agriculture, and another 181.3 million ha (25%) belong to countries that practice intensive agriculture based on chemicalization and the use of heavy machinery not suitable for chernozems, which in most cases have a medium or medium-fine grain size composition. As a result, practically all arable chernozems (31% of chernozems are cultivated globally) are affected by dehumification, destructuring-disaggregation, compaction, slitting, etc.

According to more recent calculations, arable chernozems have lost up to 50% of their initial organic carbon content globally. In addition, as a result of advanced degradation, the natural fertility of soils and the capacity for plants to capture carbon from the atmosphere and sequester it in the soil have been significantly reduced. This highlights the necessity of shifting the agricultural management paradigm of chernozem soils toward practices that prioritize the sequestration and stabilization of organic carbon through agrobiocenotic, pedoregenerative agricultural technologies.

The purpose of the present research involves the development of the methodological and conceptual-applicative conceptual framework for sustainable management of organic carbon within agrobiocenotic pedoregenerative agricultural technologies.

2. Methods

<u>Conceptual-methodological and applicative framework for sustainable management of organic carbon in chernozems.</u>

The conceptual-methodological framework for sustainable management of organic carbon in chernozems is provided by the theory of sialitic-carbonate pedogenesis, especially chernozem pedogenesis, which is the only type of pedogenesis in which the decisive role is played by the process of formation-accumulation-stabilization of organic carbon. Its achievement is favored by the moderate-temperate climate, the sialitic-carbonate nature of the alteration crust and the steppe plant associations.

In this sense, arable chernozems require a special approach to the management of fertility, health and bioproductivity, based on the management of the carbon cycle responsible for the unidirectional implementation of typogenetic processes. This requires the conformity of all agrotechnological components to the natural model of functioning of the soil ecosystem. In this context, when developing the technological model, it must be taken into account that the genesis of chernozems is determined by the process of understanding, which represents a complex macroprocess that involves the interactive, interdependent and interdetermined implementation of three elementary typogenetic processes: a) formation and accumulation of humus; b) biogenic accumulation of biophilic elements; c) aggregation-structuring of the soil mass with the formation of structural "chernozem" aggregates with a diameter of 5-1 mm. The driving force in their implementation is the process of humus formation, for the implementation of which optimal conditions are created in chernozems:

- high content (8-20 t/ha) of plant and root residues;

- presence of about 25% of leguminous species in the composition of plant associations, especially during the biologically active period (April-June);

- in the composition of organic residues from 60 to 90% belong to root residues;

- increased nitrogen content in the composition of plant residues;

- high degree of saturation of the solution and the adsorbent complex of the soil with calcium, neutral or weakly basic reaction;

- moderate microbiological activity and advanced fauna;

- pronounced contrast of the humidity regime and biohydrothermal and bioaerohydric conditions against the background of non-percolative (carbonate chernozems, typical weakly and moderately humiferous) or periodically percolative (levated and clayey alluvial chernozems).

In the context of the listed factors in the agricultural regime, not only the indispensable conditions, dependent on the biological factor, are achieved. This implies the conclusion that the management of the chernozem process in the agricultural regime must be based on the management of bioenergy resources. In light of the current trend of climatic conditions, an important element of the management of the organic carbon cycle in conditions of anthropo-natural chernozem pedogenesis is its differentiated approach, taking into account the genetic peculiarities of soils both at the higher taxonomic levels of chernozems (type, subtype, genus) and at the lower ones (species, category, etc.) as well as bioclimatic conditions (zone, subzone, biopedoclimatic district, etc.).

The concept of differentiated soil management taking into account zonal peculiarities and types/subtypes of pedogenesis is derived from the “Law on Agricultural Empires. Their relatively stable and unchangeable character within the Earth’s globe” (Aparin, 2013)**.**

In this context V.V. Docuceav in his works to unite the historical natural areas according to their general characteristics and, in particular, their agricultural characteristics and creditworthiness/value into five great "agricultural empires" that follow one another from north to south. The very names of the "empires" include the essence of the integral assessment of the natural peculiarities of the soils, in their capacity as an object of management, a condition "which was considered a priority basis for the reorganization of agricultural civilization" being elevated to the rank of law.

With reference to chernozems, they were included in the "third kingdom of physification or restoration (secondary) and use of the fine structure of chernozems". Here, specially adapted procedures are needed to restore the physification damaged by inept agricultural cultivation and to use as fully as possible the small but capricious amount of steppe water (Aparin, 2013).

With reference to fertilization, Docuceev V.V. warned "chernozems do not need chemization". In them, nutrition is contained for many millennia: they have to restore the native structure.

From the perspective of applying these principles to the differentiated management of the carbon cycle in arable chernozems of the Prut–Dniester region, our research considers chernozem pedogenesis as the result of the intertwined evolution of soil-forming and landscape processes operating at the pedological timescale throughout the Holocene. This approach also takes into account the specific pedo-ecological characteristics of the Prut–Dniester area, marked by an unstable semi-arid to semi-humid pedogenetic regime. These conditions are reflected in the variable intensity of humus accumulation, the distribution and differentiation of biopedogenetic products within the soil profile, and the sensitivity of both internal and external pedofunctional environmental factors to ongoing climate change.

Through this prism of ideas, three biopedohydrothermal spaces were identified in our research: a) forest-steppe (CHT>1), b) steppe (CHT≈0.8-0.9), c) southern steppe (CHT≈0.65-0.8), which determine the differentiated realization of chernozem typogenetic processes materialized in the genetic sequence: carbonate chernozem-typical weakly humiferous chernozem (southern steppe) - typical moderately humiferous chernozem (meadow steppe) - leached chernozem-clayoliuvial chernozem (forest-steppe) and represent a complex sequence accompanied by the concomitant modification of hydrothermal conditions, the degree of continentality of the climate and pedogenetic processes within the current climate trend (Jigău et al., 2024). At the same time, it was established that within the current trend of interdetermined and interdependent interactions [climatic conditions]↔[soil climate], the chernozem process within the biopedohydrothermal spaces and biopedoclimatic districts, into which they are divided, proceeds under conditions of aridification manifested in the lower degree of water supply induced by the intercalated action of climate change and agrogenesis (Tab. 1) (Jigău et al., 2024; Jigău et al., 2021).

At the same time, our more recent research has shown that the chernozems of the space between the Prut and the Dniester, regardless of their biopedohydrothermal space/subspace, are characterized by identical morphogenetic features: the maximum thickness of the humus-accumulative horizon (Am) about 45-48 cm, the maximum thickness of the humiferous layer (humus content > 1%) – 100-110 cm, the depth of the illuvial-carbonate horizon (Bca) (with small deviations) – 80-100 cm. In our view, this suggests the attainment of a microclimatic optimum during the Holocene formation, development, and evolution of chernozems in the Prut–Dniester region, driven by the cyclicity of climatic conditions at the pedological timescale. This process is reflected in the differentiation of three major pedological spaces and three corresponding pedohydrothermal subspaces (pedocosms). Their constitution and their stability in time and space allow us to consider that extreme states of chernozem pedogenesis within each of them are carbonate chernozems under aridifying climate conditions and clayey-illuvial ones under humidifying conditions, and the evolution of the pedogenetic profile of the soils within them involves the evolution from weakly differentiated (carbonate chernozem) to strongly differentiated (clayey-illuvial chernozem).

Within the current (anthropogenic-natural) stage of evolution of the chernozem pedogenesis in the region, the determining role of climate is reduced and the aridization impact of agrogenesis is increased. As a result, under the current trend of climatic conditions in the region, the process of chernozem pedogenesis within the limits of each pedohydrothermal space/subspace proceeds under conditions of intensive aridization manifested in a lower provision of water than that possible under the respective climatic conditions. This leads to a significant change in the meaning and intensity of the basic typogenetic processes.

Table 1 Pedogenetic effects determined by the interaction of agrogenesis and climate change.

Agrogenesis	Climate change
Intensification of the processes of mineralization of humic substances - dehumification. Negative balance of humus.	Intensification of the mineralization process of organic residues within the integral mineralization-humification process. Failure to compensate for humus losses - negative humus balance.
Destructuring due to reduction of humus content, decalcification of the arable horizon. Mechanical destruction of the structure.	Modification of soil structure and texture due to the stable tendency of degradation/alteration under the influence of extreme climatic factors and extreme conditions induced in the soil.
Soil compaction caused by mechanical pressures generated by agricultural machinery, as well as by the disaggregation and structural degradation of the soil mass.	More rigid arrangement of solid soil constituents as a result of disaggregation/alteration. Consolidation/hardening of soils as a result of excessive drying.
Increasing the intensity of the deflation process (wind erosion) as a result of the structure being broken down.	Amplification of wind erosion due to increased summer temperatures and reduced precipitation during the hot season.
Degradation of soil biota and reduction of biodiversity due to pore space degradation.	Reduction in the mass and biodiversity of soil biota as a result of increased soil temperature and reduction in useful water reserves throughout the profile thickness.
Changing the composition of the soil solution as a result of a more defective exchange of substances in the soil profile.	An increase in the concentration and alteration of the composition of the soil solution resulting from intensified soil water evaporation.
Reduction of the bioproductive function of the soil as a result of the reduction in the quantity of productive water, the intensity of biological processes and the degree of mobility and accessibility of biophilic elements.	Reduction in the quantity and quality of soil organic matter due to reduced rhizodeposition.

This highlights the need for a revised paradigm in managing the soil organic carbon cycle through the adoption of pedoregenerative agricultural systems that prioritize the restoration and reproduction of soil resources. In this context, such pedoregenerative agricultural systems are intended to simultaneously address several fundamental objectives:

a) restoring the unidirectional reproductive trend of chernozem typogenetic processes;

b) expanding the reproduction of soil fertility and health;

c) increasing resilience and capacity to adapt to more severe climate phenomena induced by climate change;

d) continuously increasing soil bioproductivity, the quantity of agri-food products and their health.

Through this prism of ideas, all agricultural activities are to be conformed to the natural model of soil functioning in concrete landscape conditions.

In this context, the pedoregenerative agricultural system represents a complex soil resource management system based on the optimization of all soil properties and regimes in order to sustain the process of plant photosynthesis, materialized in the increase of the organic carbon flux in the soil and the processes of organic matter transformation, the formation and accumulation of humus, as well as in the expanded reproduction of the chernozem process of solification. Through this prism of ideas, the sequestration and stabilization of organic carbon represents the most cost-effective and accessible procedure for increasing the resilience of soils to climate change, adapting to them, reducing the induced consequences, as well as preventing and combating the aridification and desertification of chernozems, solving, at the same time, the problems related to food security.

Integrating indices of the specified processes are the parameters of the humus state and those of the structural-aggregate state of the soils.

In the current research, the structural-aggregate analysis was carried out by the Savvinov method (Jigău & Nagacevschi, 2006). The total organic matter content and the total humus content were determined by the I.V. Tiurin method (Kauritcheva, 1980). The content of humic acid groups was determined by the I.V. Tiurin method, and the content of mobile humic substances was determined in the 0.1n NaOH extract (Krupenikov, 1992).

3. Results and discussion

<u>The state of the chernozems of the area between the Prut and the Dniester in the context of pedoregenerative agriculture</u>

The chernozems between the Prut and the Dniester are characterized by a relatively high capacity for resilience and adaptation to climate change, which is developed on the pedological scale of time and is materialized in the increased potential for capture-sequestration stabilization of organic carbon and is ensured by the favorable natural framework for the persistence of chernozem pedogenesis. In this sense, according to several researches, the current chernozems in the region represent the thirteenth final phase (at the moment) of chernozem pedogenesis during the Quaternary, otherwise identical in biopedoclimatic conditions to the previous twelve phases **(**Borisov & Baibekov, 2002**;** Lisetskiy et. all., 2013**).** At the same time, the climatic conditions are milder for agriculture, which ensures an absorption potential of up to 2-3 tons/ha/year of carbon dioxide.

The main factor limiting the realization of this potential is represented by changes in the pedogenetic and pedofunctional environment resulting from their incorporation into agricultural use, further intensified in recent times by the combined effects of climate change and agrogenesis.

Our research has shown that in the arable regime, the morphometric indices (layer thickness (Am+Bm), the thickness of the humus-accumulative horizon (Am), the thickness of the transition horizon (B) over more than 140 years, have practically not undergone significant changes, and the differences observed are within the margin of error and, probably, are subjective in nature (Tab. 2).

Table 2 Evolution of the morphometric indices of chernozems in the Prut–Dniester region during the post-Dokuchaev period.

Soil	Morphometric indices	Morphometric index values, cm					
		V. V. Docuceaev 1981		Krupenikov, 1978		CRPA*, 2011	
		M	Max	M	Max	M	Max
Typical moderately humus-rich and leached chernozems	Thickness of the humiferous layer, (Am+Bm), cm	91	137	96	125	93	133
	Thickness of the humus-accumulative horizon (Am), cm	43	51	42	47	42	49
	Thickness of the transition horizon (Bm), cm	41,0	96	40	78	42	91
	Thickness of the active root layer, cm	58	72	48	71	31	60

*Note *: the measurements were carried out as part of the activities to assess the suitability of soils for irrigation of 11 massifs with a total area of 15.6 thousand ha in the districts of Criuleni, Anenii Noi, Ungheni, Leova and Cahul. CRPA - Republican Center for Applied Pedology*

Conversely, a marked decrease in the thickness of the active root layer is observed, which, in our view, is associated with the predominant accumulation of phytonutrients in the upper and middle portions of the arable horizon, as well as with the reduced proportion of the chernozem edaphic volume (approximately 85–95 cm) effectively exploited by crop plants.

In a pedogenetic and pedofunctional context, this implies a significant reduction in the role of the root mechanism in the aggregation-structuring of arable chernozems but also a drastic reduction in bioenergetic reserves in the subarable segment (AmBm+Bm) of the profile. As a result, a stable regime of dehumification (reduction to zero of the humification process and reproduction of humus reserves) and unidirectional dehumusification caused by the mineralization of the inert humus fraction is established in this. At the same time, the predominant accumulation of plant residues in the upper segment of the profile, with a high degree of dynamics of the aerohydric and hydrothermal regimes, leads to an increase in the share of the mineralization process within the integral process of humification-mineralization of organic residues and a reduction in the quantities of newly formed humus. Under these conditions, the progressive-accumulative compensatory humiferous profile is substituted by the uncompensated regressive-accumulative humiferous profile (Lesanu & Jigau, 2012; Jigau et al., 2022). At the same time, the mentioned processes led to the accelerated modification of the humus state indices (Tab. 3) and of the physical and hydrophysical properties determined by the humus state (Tab. 4).

Table 3 Indices of the quality status of arable chernozems in Moldova.

Quality indices	Parameters		Current status of quality indices
	Optimums	Real	
Erosional:			
Soil losses, t/ha	5 (LD)	15 – 20	extremely large

Quality indices	Parameters		Current status of quality indices
	Optimums	Real	
Humus losses, kg/ha	70	700	extremely large
Nutrient losses (NP), kg/ha	10-12	50	large
Agrochemicals:			
Favorable humus content in the arable layer (0-30 cm), %	4	80% of agricultural land is characterized by humus content below 3% (low)	
Humus balance, t/ha	balanced or positive	minus 0.7	Negative
Optimal mobile phosphorus in the 0–30 cm layer, mg/100 g soil	3,0 - 4,0 (3,2 - 3,4)	60% of agricultural land is characterized by low mobile phosphorus content (< 2 mg/100 g of soil)	
Balance of biophilic elements in the soil (NPK), kg/ha	balanced or positive	minus 130-140	pronounced negatively

Table 4 Agrophysical quality indices of the arable layer of arable chernozems in the Republic of Moldova.

Quality Indices	Parameters		Quality Status
	Optimums	Real	
Aggregate instability indices	5-7	10-14	unsatisfactory
Structuring factor, %	80-92	90-94	satisfactory
Agronomically valuable aggregates 0.25-10 mm (dry fractionation), %	45-93	70-80	satisfactory
Hydrostable aggregates > 0.25 mm, (wet fractionation), %	30-60	50-70	unsatisfactory
Structuring coefficient	0,7-4,3	2,0-4,0	unsatisfactory
Hydrostability criterion, %	42-50	55-70	unsatisfactory
Bundle density, g/cm3	0,84-1,37	1,0-1,3	satisfactory
Porosity, % Total Active Aeration	 43-60 27-39 11-39	 55-60 44-46 15-20	 satisfactory unsatisfactory unsatisfactory
Water capacity, % V/V CC URC DOAU DAU	 26-30 18-24 7-13 9-20	 34-36 26-28 10-13 20-22	 unsatisfactory unsatisfactory unsatisfactory unsatisfactory

Through the prism of the theory of natural-anthropic chernozem pedogenesis, the specified changes are genetically determined and are determined by the modification of the entire genetic-evolutionary chain of the pedogenetic process: factors↔regimes↔elementary pedogenetic processes↔soil (Jigau et al., 2002). Through this prism of ideas, the inclusion of chernozems in the arable cycle is accompanied by the substitution of biocenoses with agrophytocenoses, the destruction of the steppe litter and the horizon understood, the intensification of the degree of aeration of the arable layer, etc. and leads to the modification of the entire complex of abiotic and biotic factors and, respectively, of the biopedogenetic processes manifested in the modification of the meaning and intensity of the chernozem typogenetic processes that are reflected at all hierarchical levels (micro-, meso-, macroprocesses), of pedogenesis and of structural-functional organization (elementary particle-aggregate-horizon-profile) of the soil ecosystem.

Within the newly created pedogenetic environment, significant changes are being made to the pedogenetic and pedofunctional regimes, processes, properties, functions and ecosystem services. The most receptive to these is the water balance which, as a result of the intensification of physical evaporation, is established at a lower quantitative level, manifested in the aridification of arable chernozems, materialized in the provision of water at a lower level than possible under current climatic conditions. At the same time, the predominant concentration of crop plant roots in the upper and middle segment of the arable layer causes more intensive water consumption from it. As a result, a cumulative moisture deficit has been established in the arable layer. In the lower segment of the soil profile, on the contrary, a unidirectional tendency of accumulation of moisture not consumed by evapotranspiration has been established. Thus, in arable chernozems the water regime evolves in two opposite directions: unidirectional reduction of the moisture volume in the anthropogenically modified layer and unidirectional overwetting of the lower segment of the profile (Jigău, 2023 a). The hydrological profile of arable chernozems is divided into two layers: a) aridized - the upper and middle segment of the profile with small water reserves and intensive consumption of them; b) lower - with residual trend - with excessively moistened mullat (Jigău et al., 2018).

At the same time, more recent research has shown that in the hydrological profile of arable chernozems, during the vegetation period, a secondary aridized layer is outlined with characteristic features of the "physiologically dead" layer caused by the reduction of capillary rise in the underlying layer as a result of the interruption of capillary continuity determined by the disturbance of the pore space. The capacity for water and the water conservation capacity in soils have decreased drastically. At the same time, it has been established that the specified changes are residual-cumulative in nature, and as a result, the degree of continentability of the arable chernozem climate increases considerably (Jigău et al., 2018). Thermo-hydrophysical changes have led to changes in the composition, diversity, number and mass of the soil biota. In the upper, aridized segment of the arable chernozem profile, the number and mass of microorganisms increases and the number and mass of pedomesofauna, especially earthworms, are reduced, these retreating to the middle segment and even the lower one **(**Lisetskiy et al., 2023**).** Therefore, in arable chernozems, the microbiological processes of transformation of plant residues are intensified and their mineralization energy increases by about 2 times, materialized in the disruption of the natural balance between the processes of mineralization and humification of plant residues in favor of mineralization. This led to the establishment in arable chernozems of a new bioenergetic state and, respectively, of the physical state of the soil at a lower functional level compared to unplowed chernozems (Burlacu, 2000).

The newly established bioenergetic state in arable chernozems is characterized by a reduction in the total content of organic substances in the soil and, in particular, of the labile component and as a result leads to the disruption of genetic relationships between the components of the organic substance system but also of genetic interactions between the horizons of the humus profile, as well as the unidirectional cyclicity of the general chernozem process, these being manifested in the destabilization of the soil ecosystem and the modification of the intensity and meaning of typogenetic processes.

Therefore, the reduction of the content and reserves of humus in the arable horizon is a natural consequence determined by the very fact of the inclusion of chernozems in the agricultural circuit. As a result, regions that have a long agricultural history are characterized by identical forms of soil degradation: nutrient losses as a result of their alienation with crops, humus mineralization, dehumification, destructuring, reduction of microbiotic and mesofaunal activity, compaction-overcompaction-settlement-slitting, depletion, erosion by water and wind, etc.

The integrative index of the specified processes are humus reserves in soils and an extensive comparative analysis of them using the results of measurements of the parameters of the humus state of soils in different periods showed that the chernozems in the steppe zone within the Pridanubian space even 145 years ago were characterized by organic carbon content < 4% (humus content < 7%) (Tab. 5**) (**Akhtyrtsev, 2000**).**

Table 5 The relationship between areas with different organic carbon and humus contents in the East European Plain and the associated spaces *(Lisetskiy et al., 2023).*

The region	Area (%) according to organic carbon/humus content %		
	0,5-2,0/1-3,5	2-4/3,5-7,0	4-7/7,0-12,0
Central Chernozem (Russia)	15	41	44
Moldova	31	61	7
Southern Ukraine	58	42	0
Crimea	100	0	0

According to the generalizations made at the beginning of the third millennium, within the forest-steppe of the North Moldavian Plateau and the North Steppe Plain, chernozems with a Corg content of 2-4% (3.5-7.0% humus) predominate, and within the South-Basarabian Steppe Plain, those with an organic carbon content of < 2% (humus content 3.5-5%) (Jigău et al., 2023). At the same time, it has been established that the evolution of the humus state of chernozems under agrogenesis conditions is determined by the bioclimatic conditions of the region (Tab. 6) (Akhtyrtsev, 2000).

From the data presented in Tab. 6 we find that depending on the duration of agricultural exploitation, humus losses are more intensive (about 20% relative) in the chernozems of the Central chernozem region of Russia, which are richer in humus. In our opinion, this regularity is determined by their genetic peculiarities originating from their genetic past within the genetic chain: hydromorphic soils→semihydromorphic soils→wet chernozem soils→automorphic chernozems→agrochernozems (Sharkov& Antipina, 2022).

In the case of arable soils in the area between the Prut and Dniester rivers, there is a clear trend of more intensive reduction of humus content in chernozems with shorter duration (<100 years) (about 1.5 times less) than in those with longer duration (>100 years) (Tab. 6).

Table 6 Average content (X) of organic carbon (Corg) in the Aar horizon of chernozems in the South-West of the East European Plain taking into account the number of measurements (n) [16].

The region	Maintenance mode				
	Fallow	Ploughing > 100 years	Ploughing < 100 years	Fallow for 10 years	Fallow > 100 years
Central Chernozem of Russia (X)	4,26	2,94	3,82	2,77	3,21

The region	Maintenance mode				
	Fallow	Ploughing > 100 years	Ploughing < 100 years	Fallow for 10 years	Fallow > 100 years
Central Chernozem of Russia (n)	31	48	28	33	30
Moldova: (X)	2,75	2,26	1,52	2,41	1,71
Moldova: (n)	18	30	25	17	19
Southern Ukraine: (X)	2,07	1,18	1,52	1,44	1,80
Southern Ukraine: (n)	17	26	17	16	22
Crimea (steppe zone) (X)	2,44	1,80	1,65	1,98	2,80
Crimea (southern zone) (n)	24	20	19	17	54

In our opinion, the mentioned regularity is determined by the process of arable chernozems degradation, which is supported by the phenomenon of seasonal overwetting during the biologically active period (April-June) in wet years/periods (Kurganova et al., 2021).

An analogous regularity is also observed under conditions of soil maintenance in the fallow regime: the organic carbon content (2.41%) in the n•10 variant is about 1.4 times higher than in the > 100 years variant (1.71%). At the same time, the organic carbon content in the n•10 variant is only 1.14 times lower than in the normalization variant, while in the > 100 years variant the organic carbon content is 1.61 times lower than in the normalization variant. Compared to the plowing variant > 100, the organic carbon content in the fallow variant n•10 years is 1.06 times higher and compared to the plowing variant < 100 years, the organic carbon content (1.51%) is about 1.6 times lower than in the fallow variant n•10 years.

In the case of maintaining the land in fallow > 100 years, the organic carbon content is about 1.32 times higher than in plowing > 100 years, and in the plowing variant < 100 years, the organic carbon content is 1.12 times lower than in fallow > 100 years.

From the above, we conclude that in the early phases (n•10 years) of maintaining chernozems in fallow, favorable conditions are created for the regeneration of the processes of formation-accumulation and stabilization of organic carbon in structural aggregates manifested in the progradation of arable chernozems (Tab. 7).

Table 7 Organic matter composition of typical moderately humus-rich chernozems (0-30 cm layer) under various maintenance systems.

Maintenance mode	Total organic matter content	Composition of the organic matter system % of total organic matter content		
		Humus	Non-humified organic matter	Humic substances extracted in 0.1n NaOH
Forest strip (47 years)	5,84	78,8	12,8	8,4
Fallow land 16 years	5,39	76,1	13,7	10,2
Lightly overcultivated arable land	3,68	92,8	1,4	5,3
Moderately overcultivated arable land	3,08	94,8	0,9	4,3
Heavily overcultivated arable land	2,36	96,2	0,7	3,1

From the table presented we find that the transfer of arable chernozems affected by various degradative processes into fallow regime contributes to the increase of the total organic matter content in the soil, increasing it over a short period of time (16 years) up to 5.39%, which constitutes about 92% of the total organic matter content in the soil in the Forest Strip (47 years). In its composition, 76.1% is humus and the content of labile organic substances increases up to 23.9%. Of these, the amount of non-humified organic matter constitutes 13.7% of Ctotal and the content of mobile humic substances - 10.2%. The accelerated increase in the fraction of labile humic substances in the composition of the organic substance system indicates the increased receptivity of arable chernozems to bioenergetic impacts, and the content of mobile humic substances (10.2%) indicates the intensification of the humus formation process within the integral process of mineralization-humification of plant residues.

The organic matter system of arable chernozems subjected to intensive cultivation shows generally low (3–4%) to very low (2–3%) levels of organic substances, with their quantity decreasing as the degree of overcultivation increases. Within this system, the proportion of humus becomes relatively higher and continues to rise with increasing cultivation pressure. Conversely, the fraction of labile organic compounds declines, from about 6.7% in slightly overcultivated soils to roughly 5.2% in moderately affected soils and to around 3.8% in strongly overcultivated ones.

The amount of non-humified organic material in weakly overcultivated chernozems is approximately 8–9 times lower than in uncultivated soils, while in moderately and strongly overcultivated soils it is reduced by about 12–13 times. Similarly, the content of mobile humic substances decreases by roughly two- to fourfold depending on cultivation intensity. These characteristics suggest that the organic matter systems of cultivated chernozems behave as relatively inert agrogenic formations with limited bioenergetic capacity to sustain the interrelated functioning of organic matter and soil aggregates, as well as the natural regeneration of the chernozem soil-forming process.

At the same time, both long-term uncultivated soils (around 47 years, such as those in forest shelterbelts) and more recently fallowed soils (approximately 16 years) display a fulvate-humate type of humus composition, with Cah:Caf ratios of about 1.63 and 1.86, respectively.

Humic acids predominate in the composition of humus, and calcium humates predominate in their composition. In the composition of fulvic acids - calcium fulvates. At the same time, from Table 8 we note that in forest strip conditions, despite the long period of non-cultivation, the content of total organic carbon (Ct) exceeds its content in soils recently fallowed by only 0.29%. At the same time, the content of mobile humic substances, extracted in 0.1n NaOH, in soils maintained in fallow (10.2%) exceeds the amount (8.3%) contained in the soil in the forest strip. This allows us to consider that the soil within the forest strip has reached the state of bioenergetic equilibrium at a relatively low level and subsequently the flow of fresh organic matter is consumed only when this equilibrium is reached. Therefore, the statements regarding the rehabilitation of overcultivated soils through afforestation have no experimental-applicative support. On the contrary, in the fallow regime in soils, a unidirectional trend of reproduction of the chernozem process is established (Tab. 8).

In this sense, the data presented in Table 8 show that in fallow conditions, not only the total content of humic acids is restored (45% compared to 43.2% in the forest strip) due to the fraction of stable humates (Ah3) formed with clay minerals and stable forms of sesquioxides. The intensification of the process of formation of humic acids is favored by the increase in the amount of root residues included in humification, these being the main suppliers of humic acids, as well as by the creation of a biohydrothermal and bioaerohydric framework that favors the formation of stable humic substances. In this sense, our previous research has shown that in fallow conditions, the pronounced non-percolative exudative-desuctive water regime that favors dehumification is substituted by the non-percolative desuctive-transpirative water regime.

Table 8 Composition of the humic system of typical moderately humiferous chernozems under various maintenance systems.

Maintenance mode	Total c, %	C Humic acids %					C fulvic acids				Non-hydrolyzed C,m %	Cah/Caf
		Ah1	Ah2	Ah3	Sum	Af1a	Af1	Af 2	Af3	Sum		
Forest strip	2,68	11,8	27,5	3,9	43,2	1,9	6,7	15,2	2,8	26,5	30,3	1,63
Fallow	2,39	10,7	26,5	8,0	45,2	1,9	5,5	11,9	5,0	24,3	30,5	1,86
Lightly overcultivated arable land	1,98	14,0	19,7	6,2	39,9	6,6	7,9	10,0	4,8	29,3	30,8	1,37
Moderately overcultivated arable land	1,70	14,7	17,8	4,6	37,1	7,6	8,6	10,9	4,4	31,4	31,4	1,18
Heavily overcultivated arable land	1,32	14,9	18,1	4,6	37,6	7,8	8,8	9,8	4,9	31,3	31,1	1,21

Its basic feature is the stable tendency of deep wetting and humidification of the profile with elements of excess moisture throughout the entire thickness of the profile in some years and periods of the years (mainly in spring). In such periods/years, favorable conditions are created in the soils for the humification process with the predominant formation of humic substances, as well as for the transformation of humic substance fractions (Ah1, Af1a, Af1) into more stable formations that stimulate the processes of aggregation-structuring and stabilization of organic carbon in hydrostable aggregates. In this regard, we consider that seasonal overwetting of the arable chernozem profile is one of the basic elements of the process of progradation of arable chernozems (Jigău, 2023). At the same time, the positive genetic changes in the phase of formation of humic substances in the fallow regime do not manifest themselves in the stabilization phase of newly formed humic substances in the composition of the unhydrolyzed residue, which involves a longer period of time on its pedological scale. In this regard, we mention that the multiple generalized statements that only land transfer can ensure the regeneration of the chernozem **process** (Sokolov, 1993) are not justified. Moreover, the generalized research in **(**Jigău et al., 2024**)** have shown that the subsequent re-introduction of land into the agricultural circuit leads to the degradation, in a short time, of the humus state, the structural-aggregate state and other physical properties. Based on this, we consider that the transfer of land into a fallow regime can be carried out only on limited spaces whose use for the purpose of agricultural production is not appropriate. This implies the need to review the paradigms of agricultural technologies practiced in order to comply with the imperative of climate neutrality by regenerating chernozem typogenetic processes. In this regard, we mention that according to our research, alternative agricultural systems practiced in contemporary agriculture involve only some pedoregenerative elements (Tab. 9).

Table 9 Composition of the humic system of typical moderately humiferous chernozem depending on the maintenance system (layer 0-50cm), % of Ctotal. (average data 2011-2015).

Humic components	Maintenance mode				
	Forest strip	Plowing	Chisel work	Shallow work	No-till
Total C, %	2,58	1,98	2,00	2,03	2,04
C mobile humic substances	8,76	4,46	7,02	9,12	10,36

C water-soluble humic substances	0,85	0,80	0,82	0,83	0,85
C humic acids	39,64	36,94	38,06	38,33	38,11
C fulvic acids	20,18	26,90	23,82	22,11	20,38
C crumbly humus	30,57	30,90	30,28	29,61	30,30
Cah:Caf	1,96	1,37	1,60	1,73	1,87

From the data presented in Table 9, we find that in all three systems of minimizing soil work, compared to plowing, there is a tendency to increase the organic carbon content as their reduction from partial (chisel work) to No-till. At the same time, we find that over 5 years this increase amounted to 0.014%/year in chisel work, 0.02%/year in superficial work and 0.022% year in No-till. At the same time, in the "conservative" works compared to plowing, the content of mobile humic substances increases by about 1.6 times in chisel work, by about 2 times in superficial work and by about 2.3 times in No-till. This allows us to consider that under conditions of minimizing soil work, bioaerohydric and biohydrothermal regimes are established that favor the intensification of the humification process within the integral process of mineralization-humification of organic residues with the formation of relatively stable mobile humic substances. In this sense, the Corg content of water-soluble humic substances remains practically identical for all 5 tested variants. We can therefore consider that the newly formed humic substances are included in relatively stable organo-mineral compounds insoluble in water. Within the superficial tillage and No-till variants, the intensity of humification processes is even higher than within the forest strip. At the same time, however, from Table 9 we find that the organic carbon content of the unhydrolyzed residue in all 5 variants is identical, which allows us to consider that at the current stage of evolution of the soils investigated within the "conservative" tillage systems the humification process is not accompanied by the stabilization of newly formed humic substances. At the same time, we find that the process of restoring the humic system of typical weakly humiferous chernozems, even in the case of the No-till variant, proceeds extremely slowly so that to reach the level of Corg content in the soils within the forest strip a minimum of 25 years are required, although a period of 10-12 years is required to restore the composition of the humic system (Cah:Caf). In our opinion, the main factor limiting the process of quantitative restoration of the humic system is the advanced degree of physical degradation of the chernozems in the region manifested in the structural-aggregate composition. In this regard, our previous research has shown that the negative transformation of the structural-aggregate composition of chernozems in the arable regime is the main direct cause of their physical degradation because the transformation of the structure is accompanied by a reduction in the total amount of accumulated organic matter and a change in its location in the composition of structural formations manifested in the dynamics of the structural-aggregate composition during the vegetation period (Tab. 10).

Table 10 Dynamics of the parameters of the structural-aggregate composition of typical moderately humiferous chernozem under various maintenance conditions (Average data 2011-2015).

Maintenance method Depth, cm	Depth cm	At the beginning of the growing season					At the end of the growing season				
		Dimensions of the aggregates, mm					Aggregate dimensions, mm Aggregate content, %				
		Aggregate content, %									
		> 10 mm	10-0,25 mm	5-1 mm	3-0,25 mm	< 0,25 mm	> 10 mm	10-0,25 mm	5-1 mm	3-0,25 mm	< 0,25 mm
Forest strip	0-20	7,0	89,0	52,5	48,7	4,0	14,7	78,8	43,0	47,6	6,5
	20-40	10,8	89,1	37,6	12,8	0,2	23,0	76,3	43,5	23,2	0,7
	40-50	7,4	91,9	42,9	17,9	0,7	10,4	89,0	45,2	24,2	0,9
Ploughing	0-20	4,1	89,6	55,9	53,2	6,3	6,9	83,3	47,1	51,3	9,8

	20-40	10,1	87,9	50,5	33,3	2,0	29,8	66,5	33,5	23,1	3,7
	40-50	11,8	86,3	60,6	41,9	1,9	14,4	83,4	49,3	30,9	2,2
Chisel work	0-20	17,8	83,04	45,8	43,9	5,2	26,8	69,7	39,6	40,4	3,5
	20-40	21,8	77,1	38,3	21,0	1,1	29,8	69,5	37,4	18,7	0,7
	40-50	15,3	82,8	50,8	31,54	2,0	16,9	83,5	47,4	23,8	0,5
Shallow work	0-20	15,3	83,4	55,1	18,1	1,3	9,5	81,5	40,6	37,8	9,0
	20-40	11,6	80,4	48,0	22,6	1,2	19,1	76,3	46,6	43,0	4,7
	40-50	15,8	82,7	43,5	31,5	1,4	18,4	76,7	41,3	31,8	4,9
No-till	0-20	8,8	85,7	53,6	52,8	5,6	22,4	69,7	48,2	37,4	7,8
	20-40	3,2	95,6	59,9	35,2	1,2	28,0	68,9	31,0	25,4	3,1
	40-50	19,3	79,9	44,3	26,1	0,8	15,2	83,4	43,0	26,9	1,4

From the data presented in Table 10, we mention, first of all, the increased degree of variability of the content of structural aggregate fractions with various functions, including that of sequestration-stabilization of newly formed humus; during the vegetation period. In this regard, we draw attention to the fact that a clearly outlined law of unidirectional evolution of the structural-aggregate composition in accordance with the evolution of the internal pedogenetic environment characteristic of the understood chernozems is not achieved. Moreover, this law is not achieved even in the case of long-uncultivated soils within the forest strip. This allows us to conclude that the unidirectional, interdetermined and interdependent evolution between the humic and aggregate systems is characteristic only of native chernozems and is determined by the functioning process of natural ecosystems in their capacity as "specialized" symbiotic biocenoses depending on the type of nutrition (phytocenosis-zoocenosis-pedocenosis) integrated into a closed metabolic cycle/closed functional space. Through this prism of ideas within the pedoregenerative agricultural system as a way to establish agricultural ecosystems should serve natural ecosystems. In this sense, the model of pedoregenerative development in agriculture needs to be based on the structural features of the functioning of natural ecosystems, but with the alienation of the biology of the crop from the circuit. Ensuring the sustainability of the agricultural system depends not so much on technological changes as on systemic changes. The higher the structural and functional diversity of the agroecosystem, that is, similar to the natural ecosystem, the greater the probability of ensuring the goal of climate neutrality.

In this sense, the basic criterion of modern sustainable pedoregenerative agriculture involves shifting the emphasis from the needs of the plant (currently practiced) to the needs of the soil.

This involves reviewing the paradigm of the integral process of agricultural production. In accordance with its basic conceptual principles, regardless of the production system practiced, the main means of production in agriculture are the soil (paraviviun bioroutine system) and the plants integrated into the ecological system "soil-plant" which provide the bioenergetic resources (soil fertility) and the functional framework (soil health) for the expanded unidirectional reproduction of pedogenesis.

Therefore, the integral process of agricultural production involves the integration with maximum efficiency of the biological processes carried out in the "soil-plant" system, determined by environmental conditions, especially climatic conditions. In this regard, for the first time, it was established that humidity to a greater extent determines the qualitative component - the meaning of the pedogenetic process, and the thermal factor determines the quantitative component - the intensity of the pedogenetic process (Sokolov, 1993).

Through this prism of ideas, the laws of pedo-ecological interactions (i.e., of “soil-environment/soil-plant” interactions) are determined by hydrothermal conditions, these being a function of the physical soil composition (Jigău et al., 2024). Therefore, the agricultural production process cannot be managed by neglecting the physical properties of soils that determine the operating framework of the “soil-plant” system and the agro-landscape conditions. In reality, however, the current concept of agricultural production is based only on the use and restoration of soil fertility, which is perceived only through the prism of its capacity to provide plants with the nutrients necessary for their growth and development, with emphasis placed on mineral fertilization, i.e., on the intensification of the abiotic factor. Through this prism of ideas, soil health and its fertility are interdependent and interdetermined biophysical categories, and their management requires a systemic approach within an agrobiocenotic pedo-regenerative agricultural system that includes:

1. Adaptation of all components of the agricultural system: soil cultivation, structure of agrophytocenoses, fertilization system to the specific landscape conditions.

2. Rational management of stubble and plant residues as a bioenergy source and mulch. From the perspective of the theory of anthropo-natural chernozem pedogenesis, it fulfills the function of providing energy and nutrition.

3. Soil cultivation at depths that will not exceed the depth of seed incorporation or their exclusion.

4. Keeping 60-65% of stubble and not less than 30% of plant residues on the soil surface.

5. Practicing sidereal (as appropriate) and "green" arable land.

6. Cultivation of phytoameliorative cover crops or intercrops.

7. Restoring the organic system of the soil and its functionality, and ensuring a positive trend in the humus balance.

8. Monitoring the soil nutrition regime at the end of vegetation, conforming the amounts of fertilizers to the needs of the soil and their differentiated administration, taking into account both the humus content in the soil and that of humiferous detritus.

9. Ensuring biological nitrogen sources for the functioning of the soil microbiome and carrying out the humification process, through the use of bioorgano-mineral products of humic origin and the administration of algal preparations.

10. Root rotation and promoting biological soil loosening processes. Practicing mechanical loosening only in exceptional cases. Sustaining the root and coprolitic mechanisms of self-loosening and aggression-structuring of the soil mass.

11. Cultivation of varieties and hybrids adaptable to the practiced tillage system:

a) The minimum tillage system with mulches imitating the natural soil formation process.

b) The minimum tillage system only in the row with mulch without working the space between the rows (Strip-till).

c) Direct sowing (No-till).

5. Conclusion

Within the current trend of the chernozem process determined by the intercalated action of agrogenesis and climate change, the degradative processes induced by it have caused a series of biopedoclimatic and pedofunctional changes with a decisive impact on the meaning and intensity of the chernozem typogenetic processes. Under these conditions, the management of chernozems is faced with a series of challenges that compromise the process of reproduction of the typogenetic processes materialized in the reduction of the capacity to sequester and stabilize organic carbon:

1. The soils no longer correspond to the current climatic conditions (a phenomenon unknown to the theory of pedogenesis);
2. The soils, as a result of the reduction of the adaptive capacity, no longer cope with the current climatic conditions;
3. The soils no longer correspond to the practiced technologies and vice versa - the practiced technologies no longer correspond to the state of the soils;
4. None of the currently practiced technologies ensures the reproduction of the chernozem pedogenetic process and the capacity to adapt to the current set of climatic conditions.

In this sense, it was established that afforestation works (47 years) and the transfer of land to fallow regime (16 years) ensure the restoration of organic carbon content in the soil below the level of its initial content.

This involves changing the paradigm of the applied technology framework by placing emphasis on the regeneration of the capacity to adapt to newly formed climatic conditions and the environmental-modeling function materialized in reducing the impact of degradative processes on the "soil-factors" relationships within some agrobiocenotic pedoregenerative technologies. From the perspective of the theory of chernozem pedogenesis, the regeneration of the chernozem process within pedoregenerative technologies involves two successive natural-anthropological-evolutionary stages: a) rehabilitation and b) regeneration.

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